Measurement of the CP-violating phase s in B¯0s→D+sD−s decays

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Measurement of the CP-violating phase ϕ_s in $\overline{B}{}^0_s \to D_s^+ D_s^-$ decays

The LHCb collaboration[†]

Abstract

We present a measurement of the CP-violating weak mixing phase ϕ_s using the decay $\overline{B}{}^0_s \to D_s^+ D_s^-$ in a data sample corresponding to $3.0\,\mathrm{fb}^{-1}$ of integrated luminosity collected with the LHCb detector in pp collisions at centre-of-mass energies of 7 and 8 TeV. An analysis of the time evolution of the system, which does not use the constraint $|\lambda| = 1$ to allow for the presence of CP violation in decay, yields $\phi_s = 0.02 \pm 0.17\,(\mathrm{stat}) \pm 0.02\,(\mathrm{syst})\,\mathrm{rad}$, $|\lambda| = 0.91\,^{+0.18}_{-0.15}\,(\mathrm{stat}) \pm 0.02\,(\mathrm{syst})$. This result is consistent with the Standard Model expectation.

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The CP-violating weak mixing phase ϕ_s can be measured in the interference between mixing and decay of $\overline{B}{}^0_s$ mesons to CP eigenstates that proceeds via the $b \to c\bar{c}s$ transition, and is predicted to be small in the Standard Model (SM): $\phi_s^{\rm SM} \approx -2\beta_s \equiv -2\arg\left(-\frac{V_{ts}V_{tb}{}^*}{V_{cs}V_{cb}{}^*}\right) = -36.3^{+1.6}_{-1.5}\,\text{mrad}$ [1]. Measurements of ϕ_s are sensitive to the effects of potential non-SM particles contributing to the B^0_s-$\overline{B}{}^0_s$ mixing amplitude. Several measurements of ϕ_s have been made with the decay mode $\overline{B}{}^0_s \to J/\psi\,\phi$, with the first results showing tension with the SM expectation [2,3]. Since then, more recent measurements of ϕ_s have found values consistent with the SM prediction in $\overline{B}{}^0_s \to J/\psi\,K^+K^-$ and $\overline{B}{}^0_s \to J/\psi\,\pi^+\pi^-$ decays [4–8]. The world average value determined prior to the publication of Ref. [5] is $\phi_s = 0 \pm 70\,\text{mrad}$ [9].

Precise measurements of ϕ_s are complicated by the presence of loop (penguin) diagrams, which could have an appreciable effect [10]. It is therefore important to measure ϕ_s in additional decay modes where penguin amplitudes may differ [11]. Additionally, in the $\overline{B}{}^0_s \to J/\psi\,\phi$ channel, where a spin-0 meson decays to two spin-1 mesons, an angular analysis is required to disentangle statistically the CP-even and CP-odd components. The decay $\overline{B}{}^0_s \to D_s^+D_s^-$ is also a $b \to c\bar{c}s$ transition with which ϕ_s can be measured [12], with the advantage that the $D_s^+D_s^-$ final state is CP-even, and does not require angular analysis.

In this Letter, we present the first measurement of ϕ_s in $\overline{B}{}^0_s \to D_s^+D_s^-$ decays using an integrated luminosity of $3.0\,\text{fb}^{-1}$, obtained from pp collisions collected by the LHCb detector. One third of the data were collected at a centre-of-mass energy of $7\,\text{TeV}$, and the remainder at $8\,\text{TeV}$. We perform a fit to the time evolution of the $\overline{B}{}^0_s$-B^0_s system in order to extract ϕ_s.

LHCb is a single-arm forward spectrometer at the LHC designed for the study of particles containing b or c quarks in the pseudorapidity range 2 to 5 [13]. Events are selected by a trigger consisting of a hardware stage that identifies high transverse energy particles, followed by a software stage, which applies a full event reconstruction [14]. A multivariate algorithm [15] is used to select candidates with secondary vertices consistent with the decay of a b hadron.

Signal $\overline{B}{}^0_s \to D_s^+D_s^-$ candidates are reconstructed in four final states: (i) $D_s^+ \to K^+K^-\pi^+$, $D_s^- \to K^-K^+\pi^-$; (ii) $D_s^+ \to K^+K^-\pi^+$, $D_s^- \to \pi^-\pi^+\pi^-$; (iii) $D_s^+ \to K^+K^-\pi^+, D_s^- \to K^-\pi^+\pi^-$; and (iv) $D_s^+ \to \pi^+\pi^-\pi^+, D_s^- \to \pi^-\pi^+\pi^-$. Inclusion of charge-conjugate processes, unless otherwise specified, is implicit. The $B^0 \to D^-D_s^+$ decay mode, where $D^- \to K^+\pi^-\pi^-$, and $D_s^+ \to K^+K^-\pi^+$, is used as a control channel. The selection requirements follow Ref. [16], apart from minor differences in the particle identification requirements and $B_{(s)}$ candidate mass regions. $D_{(s)}$ meson candidates are required to have masses within $25\,\text{MeV}/c^2$ of their known values [17] and to have a significant separation from the $B_{(s)}$ vertex. As the signatures of b-hadron decays to double-charm final states are all similar, vetoes are employed to suppress the cross-feed resulting from particle misidentification, following Ref. [18]. All $B_{(s)}$ candidates are refitted, taking both $D_{(s)}$ mass and vertex constraints into account [19]. A boosted decision tree (BDT) [20,21] is used to improve the signal to background ratio. The BDT is trained with simulated decays to emulate the signal, and same-charge $D_s^+D_s^+$ and $D^+D_s^+$ from candidates with masses on the range

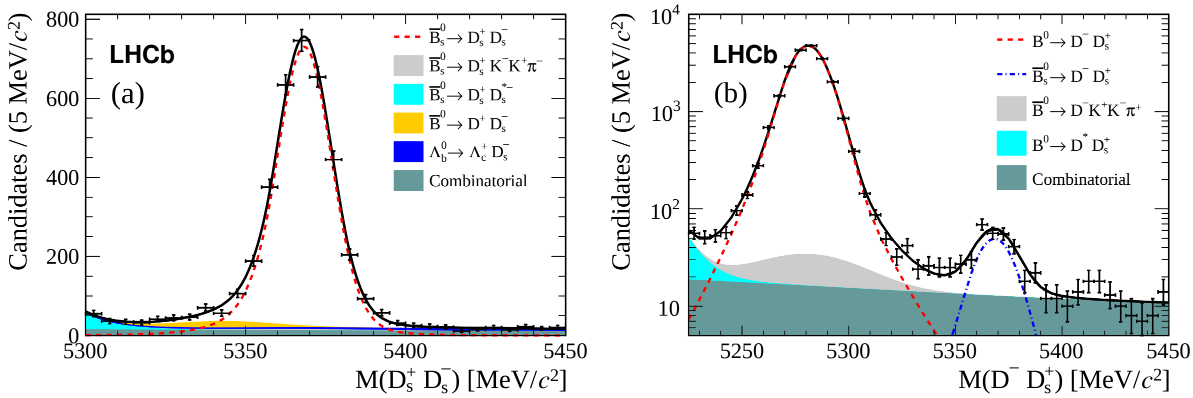

Figure 1: Invariant mass distributions of (a) $\overline{B}{}^0_s \to D_s^+ D_s^-$ and (b) $B^0 \to D^- D_s^+$ candidates. The points show the data; the individual fit components are indicated in the legend; the black curve shows the overall fit.

$5200 < M(D_s^+ D_s^+) < 5650\,\text{MeV}/c^2$ and $5200 < M(D^+ D_s^+) < 5600\,\text{MeV}/c^2$, respectively. The selection requirement on the BDT output, which retains about 98% of the signal events, is chosen to minimise the expected relative uncertainty in the $\overline{B}{}^0_s \to D_s^+ D_s^-$ yield. The $B_{(s)}$ candidates are required to lie in the mass regions $5300 < M(D_s^+ D_s^-) < 5450\,\text{MeV}/c^2$ for the signal and $5200 < M(D^- D_s^+) < 5450\,\text{MeV}/c^2$ for the control channel, where the lower bound is chosen to suppress background contributions from $B_{(s)}$ decays with excited charm mesons in the final state. The decay time distribution is fitted in the range $0.2 < t < 12.0\,\text{ps}$ where the lower bound is chosen to reduce backgrounds from particles originating from the primary vertex.

The mass distributions for the signal, summed over the four final states, and the control channel are shown in Fig. 1, with results of unbinned maximum likelihood fits overlaid. The signal shapes are parameterised by the sum of two asymmetric Gaussian functions with a common mean. The background shapes are obtained from simulation [22–25]. Background rates from misidentified particles are obtained from $D^{*+} \to D^0 \pi^+$, $D^0 \to K^- \pi^+$ calibration data. Signal and background components are described in Ref. [16]. All yields in the fits to the full data sample are allowed to vary, except that corresponding to $\bar{B}{}^0_{(s)} \to D_{(s)}^+ K^- K^+ \pi^-$ decays, which is fixed to be 1% of the signal yield as determined from a fit to the D_s mass sidebands. We observe 3345 ± 62 $\overline{B}{}^0_s \to D_s^+ D_s^-$ signal and $21\,320 \pm 148$ $B^0 \to D^- D_s^+$ control channel decays. In the $D^- D_s^+$ channel, we also observe a contribution from $\overline{B}{}^0_s \to D_s^+ D^-$ as reported previously [18]. We use the *sPlot* technique [26] to obtain the decay time distribution of $\overline{B}{}^0_s \to D_s^+ D_s^-$ signal decays where the $D_s^+ D_s^-$ invariant mass is the discriminating variable. A fit to the background-subtracted distribution of the decay time, t, is performed using the signal-only decay time probability density function (PDF). The negative log likelihood to be minimised is

$$-\ln \mathcal{L} = -\alpha \sum_i^N W_i \ln \mathcal{P}(t_i, \delta_i, q_i^{\text{tag}} | \eta_i^{\text{tag}}), \tag{1}$$

where N denotes the total number of signal and background candidates in the fit region, W_i is the signal component weight and $\alpha = \sum_i^N W_i / \sum_i^N W_i^2$ [27]. The invariant mass is not correlated with the reconstructed decay time or its uncertainty, nor with flavour tagging output, for signal and background. The signal PDF, $\mathcal{P}$, includes detector resolution and acceptance effects and requires knowledge of the B_s^0 ($\overline{B}_s^0$) flavour at production,

$$\mathcal{P}(t, \delta, q^{\text{tag}}|\eta^{\text{tag}}) = R(\hat{t}, q^{\text{tag}}|\eta^{\text{tag}}) \otimes G(t - \hat{t}|\delta) \times \epsilon_{\text{data}}^{D_s^+ D_s^-}(t), \tag{2}$$

where $\hat{t}$ is the decay time in the absence of resolution effects, $R(\hat{t}, q^{\text{tag}}|\eta^{\text{tag}})$ describes the rate including imperfect knowledge of the initial $\overset{(-)}{B}{}_s^0$ flavour through the flavour tag, q^{tag}, and the wrong-tag probability estimate η^{tag}. The flavour tag, q^{tag}, is -1 for $\overline{B}_s^0$, $+1$ for B_s^0 and zero for untagged candidates. The calibrated decay time resolution is $G(t - \hat{t}|\delta)$ where δ is the decay time error estimate, and $\epsilon_{\text{data}}^{D_s^+ D_s^-}(t)$ is the decay time acceptance.

Allowing for *CP* violation in decay, the decay rates of $\overset{(-)}{B}{}_s^0$ mesons ignoring detector effects can be written as

$$\begin{aligned}
\Gamma(\hat{t}) = \mathcal{N} e^{-\Gamma_s \hat{t}} \Bigg[& \cosh\left(\frac{\Delta\Gamma_s}{2}\hat{t}\right) - \frac{2|\lambda|\cos\phi_s}{1+|\lambda|^2}\sinh\left(\frac{\Delta\Gamma_s}{2}\hat{t}\right) \\
& + \frac{1-|\lambda|^2}{1+|\lambda|^2}\cos(\Delta m_s \hat{t}) - \frac{2|\lambda|\sin\phi_s}{1+|\lambda|^2}\sin(\Delta m_s \hat{t}) \Bigg],
\end{aligned} \tag{3}$$

$$\begin{aligned}
\bar{\Gamma}(\hat{t}) = \left|\frac{p}{q}\right|^2 \mathcal{N} e^{-\Gamma_s \hat{t}} \Bigg[& \cosh\left(\frac{\Delta\Gamma_s}{2}\hat{t}\right) - \frac{2|\lambda|\cos\phi_s}{1+|\lambda|^2}\sinh\left(\frac{\Delta\Gamma_s}{2}\hat{t}\right) \\
& - \frac{1-|\lambda|^2}{1+|\lambda|^2}\cos(\Delta m_s \hat{t}) + \frac{2|\lambda|\sin\phi_s}{1+|\lambda|^2}\sin(\Delta m_s \hat{t}) \Bigg],
\end{aligned} \tag{4}$$

where $\Gamma_s \equiv (\Gamma_{\text{L}} + \Gamma_{\text{H}})/2$ is the average decay width of the light and heavy mass eigenstates, $\Delta\Gamma_s \equiv \Gamma_{\text{L}} - \Gamma_{\text{H}}$ is their decay width difference and $\Delta m_s \equiv m_{\text{H}} - m_{\text{L}}$ is their mass difference. As Δm_s is large [28] and the production asymmetry is small [29], the effect of the production asymmetry is negligible and so the constant $\mathcal{N}$ is the same for both B_s^0 and $\overline{B}_s^0$ mesons. Similarly we do not consider a tagging asymmetry in the fit as this is known to be consistent with zero. *CP* violation in mixing and decay is parameterised by the factor $\lambda \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}$, with $\phi_s \equiv -\arg(\lambda)$. The terms A_f ($\bar{A}_f$) are the amplitudes for the B_s^0 ($\overline{B}_s^0$) decay to the final state f, which in this case is $f = D_s^+ D_s^-$, and the complex parameters $p = \langle B_s^0 | B_L \rangle$ and $q = \langle \overline{B}_s^0 | B_L \rangle$ relate the mass and flavour eigenstates. The factor $|p/q|^2$ in Eq. (4) is related to the flavour-specific *CP* asymmetry, a_{sl}^s, by

$$a_{\text{sl}}^s = \frac{|p/q|^2 - |q/p|^2}{|p/q|^2 + |q/p|^2} \approx |p/q|^2 - 1. \tag{5}$$

LHCb has measured $a_{\text{sl}}^s = (-0.06 \pm 0.50\,(\text{stat}) \pm 0.36\,(\text{syst}))\%$ [30], implying $|p/q|^2 = 0.9994 \pm 0.0062$. We assume that it is unity in this analysis and that any observed deviation of $|\lambda|$ from 1 is due to *CP* violation in the decay, *i.e.* $|\bar{A}_f / A_f| \neq 1$.

The initial flavor of the signal b hadron is determined using two methods. In hadron collisions, b hadrons are mostly produced as pairs: the opposite-side (OS) tagger [31]

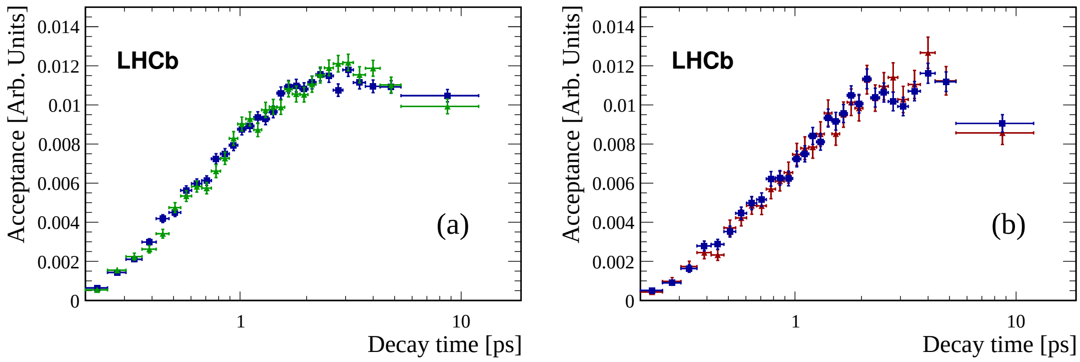

Figure 2: Decay time acceptances in simulation and data: (a) the $B^0 \to D^- D_s^+$ acceptance in data (green triangles) and simulation (blue squares), (b) the $\overline{B}{}_s^0 \to D_s^+ D_s^-$ acceptance in simulation (blue squares) and the $B^0 \to D^- D_s^+$ acceptance corrected for $\overline{B}{}_s^0 \to D_s^+ D_s^-$ (red triangles). The correction is described in detail in the text.

determines the flavour of the other b hadron in the event by identifying the charges of the leptons and kaons into which it decays, or the net charge of particles forming a detached vertex consistent with that of a b hadron. The neural network same-side (SS) kaon tagger [4] exploits the hadronisation process in which the fragmentation of a $\bar{b}(b)$ into a $B_s^0(\overline{B}{}_s^0)$ meson leads to an extra $\bar{s}(s)$ quark, which often forms a $K^+(K^-)$ meson, the charge of which identifies the initial $\overset{(-)}{B}{}_s^0$ flavour. The SS kaon tagger uses an improved algorithm with respect to Ref. [4] that enhances the fraction of correctly tagged mesons by 40%. In both tagging algorithms a per-event wrong-tag probability estimate, $\eta^{\rm tag}$, is determined, based on the output of a neural network trained on either simulated $\overline{B}{}_s^0 \to D_s^+ \pi^-$ events for the SS tagger, or, in the case of the OS algorithm, using a data sample of $B^- \to J/\psi K^-$ decays. The taggers are then calibrated in data using flavour-specific decay modes in order to provide a per-event wrong-tag probability, $\overset{(-)}{\omega}(\eta^{\rm tag})$, for an initial flavour $\overset{(-)}{B}{}_s^0$ meson. The calibration is performed separately for the two tagging algorithms, which are then combined in the fit. The effective tagging power is parameterised by $\varepsilon_{\rm tag} D^2$ where $D \equiv (1-2\omega)$ and $\varepsilon_{\rm tag}$ is the fraction events tagged by the algorithm.

The combined effective tagging power is $\varepsilon_{\rm tag} D^2 = (5.33 \pm 0.18\,({\rm stat}) \pm 0.17\,({\rm syst}))\%$, comparable to that of other recent analyses [32]. The rate expression including flavour tagging is

$$\begin{aligned} R(\hat{t}, q^{\rm OS}|\eta^{\rm OS}, q^{\rm SS}|\eta^{\rm SS}) = \; & (1+q^{\rm OS}[1-2\omega^{\rm OS}])(1+q^{\rm SS}[1-2\omega^{\rm SS}])\Gamma(\hat{t}) + \\ & (1-q^{\rm OS}[1-2\bar{\omega}^{\rm OS}])(1-q^{\rm SS}[1-2\bar{\omega}^{\rm SS}])\bar{\Gamma}(\hat{t}). \end{aligned} \tag{6}$$

The track reconstruction, trigger and selection efficiencies vary as a function of decay time, requiring that an acceptance function is included in the fit. The $\overline{B}{}_s^0 \to D_s^+ D_s^-$

acceptance is determined using

$$\varepsilon_{\text{data}}^{D_s^+D_s^-}(t) = \varepsilon_{\text{data}}^{D^-D_s^+}(t) \times \frac{\varepsilon_{\text{sim}}^{D_s^+D_s^-}}{\varepsilon_{\text{sim}}^{D^-D_s^+}}(t), \tag{7}$$

where $\varepsilon_{\text{data}}^{D^-D_s^+}(t)$ is the efficiency associated with the $B^0 \to D^-D_s^+$ control channel as determined directly from the data and $\varepsilon_{\text{sim}}^{D_s^+D_s^-}/\varepsilon_{\text{sim}}^{D^-D_s^+}(t)$ is the relative efficiency obtained from simulation after all selections are applied. This correction accounts for the differences in lifetime as well as small kinematic differences between the signal and control channels. The first factor in Eq. (7) is

$$\varepsilon_{\text{data}}^{D^-D_s^+}(t) = \frac{N_{\text{data}}^{D^-D_s^+}(t)}{\mathcal{N}e^{-\Gamma_d\hat{t}} \otimes G(t-\hat{t}|\sigma_{\text{eff}})}, \tag{8}$$

where $N_{\text{data}}^{D^-D_s^+}(t)$ denotes the number of $B^0 \to D^-D_s^+$ signal decays in a given bin of the decay time distribution, $\mathcal{N}e^{-\Gamma_d\hat{t}}$ is an exponential with decay width equal to that of the world average value for B^0 mesons [17], $\mathcal{N}$ is a constant and $G(t-\hat{t}|\sigma_{\text{eff}})$ is a Gaussian resolution function with width $\sigma_{\text{eff}} = 54\,\text{fs}$, determined from simulation. In the fit, the acceptance is implemented as a histogram. The binning scheme is chosen to maintain approximately equal statistical power in each bin. Figure 2(a) shows $\varepsilon_{\text{data}}^{D^-D_s^+}(t)$ and $\varepsilon_{\text{sim}}^{D^-D_s^+}(t)$, while Fig. 2(b) shows $\varepsilon_{\text{sim}}^{D_s^+D_s^-}(t)$ and $\varepsilon_{\text{data}}^{D_s^+D_s^-}(t)$ as used in the fit to extract ϕ_s. The procedure is verified by fitting for the decay width in both the signal and the control channels, where the results are found to be consistent with the published values.

The fit to determine ϕ_s uses a decay time uncertainty estimated in each event and obtained from the constrained vertex fit from which the decay time is determined. The resolution function is

$$G(t-\hat{t}|\delta) = \frac{1}{\sqrt{2\pi}\sigma(\delta)} e^{-\frac{1}{2}\left(\frac{t-\hat{t}}{\sigma(\delta)}\right)^2}. \tag{9}$$

The per-event resolution, $\sigma(\delta)$, is calibrated using simulated signal decays by fitting the effective resolution, σ_{eff}, in bins of the per-event decay time error estimate, $\sigma_{\text{eff}} = q_0 + q_1\delta$. The effective resolution is determined by fitting to the event-by-event decay time difference between the reconstructed and generated decay time in simulated signal decays. The effective resolution is the sum in quadrature of the widths of two Gaussian functions contributing with their corresponding fractions. The values $q_0 = 8.9 \pm 1.3\,\text{fs}$ and $q_1 = 1.014 \pm 0.036$ are obtained from the fit, resulting in a calibrated effective resolution of 54 fs.

In the fits that determine ϕ_s, we apply Gaussian constraints to the average decay width, $\Gamma_s = 0.661 \pm 0.007\,\text{ps}^{-1}$, the decay width difference, $\Delta\Gamma_s = 0.106 \pm 0.013\,\text{ps}^{-1}$ [4], the mixing frequency, $\Delta m_s = 17.168 \pm 0.024\,\text{ps}^{-1}$ [28] and the flavour tagging and resolution calibration parameters. The correlation between Γ_s and $\Delta\Gamma_s$ is accounted for in the fit. Two fits to the data are performed, one assuming no *CP* violation in decay, *i.e.* $|\lambda| = 1$, and a second where this assumption is removed. The fit is validated using pseudoexperiments and simulated LHCb events.

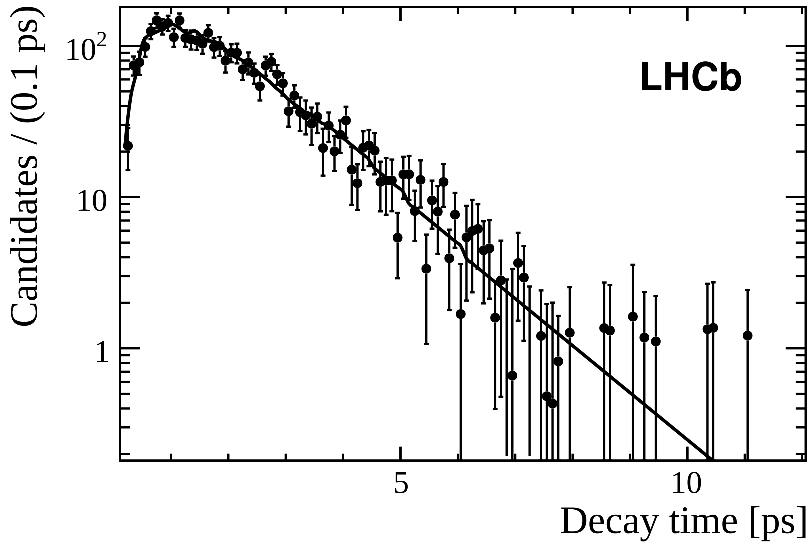

Figure 3: Distribution of the decay time for $\overline{B}{}^0_s \to D_s^+ D_s^-$ signal decays with background subtracted using the *sPlot* method, along with the fit as described in the text. Discontinuities in the fit line shape are a result of the binned acceptance.

Table 1: Summary of systematic uncertainties not already accounted for in the fit, where σ denotes the statistical uncertainty.

Systematic uncertainty	ϕ_s ($\lvert\lambda\rvert = 1$)	ϕ_s	$\lvert\lambda\rvert$
Resolution	$\pm 0.098\ \sigma$	$\pm 0.094\ \sigma$	$\pm 0.100\ \sigma$
Mass	$\pm 0.044\ \sigma$	$\pm 0.043\ \sigma$	$\pm 0.010\ \sigma$
Acceptance (model)	$\pm 0.022\ \sigma$	$\pm 0.027\ \sigma$	$\pm 0.027\ \sigma$
Acceptance (stat.)	$\pm 0.013\ \sigma$	$\pm 0.013\ \sigma$	$\pm 0.014\ \sigma$
Background subtraction	$\pm 0.009\ \sigma$	$\pm 0.008\ \sigma$	$\pm 0.046\ \sigma$
Total	$\pm 0.11\ \sigma$	$\pm 0.11\ \sigma$	$\pm 0.11\ \sigma$

The systematic uncertainties on ϕ_s and $|\lambda|$ that are not accounted for by the use of Gaussian constraints are summarised in Table 1. The systematic uncertainty associated with the resolution calibration in simulated events is studied by generating pseudoexperiments with an alternative resolution parameterisation ($q_0 = 0$, $q_1 \in [1.25, 1.45]$ [28]) obtained in $\overline{B}{}^0_s$ decays in data. The effect of mismodelling of the mass PDF is studied by fitting using a larger mass window and including an additional background component from $\overline{B}{}^0_s \to D_s^{*+} D_s^{*-}$. The effect of mismodelling the acceptance distribution is studied by fitting the $\overline{B}{}^0_s \to D_s^+ D^-$ derived acceptance in pseudoexperiments generated with the acceptance distribution determined entirely from $\overline{B}{}^0_s \to D_s^+ D_s^-$ simulation. The uncertainty due to the finite size of the simulated data samples used to determine the acceptance correction is evaluated by fitting to the data 500 times with Gaussian fluctuations around the bin values with a width equal to the statistical uncertainties. We evaluate the uncertainty due to the use of the *sPlot* method for background subtraction by fitting to simulated events, once with only signal candidates, and again to the *sPlot* determined from a mass fit to a sample containing the signal and background in proportions determined from data.

Assuming no *CP* violation in decay, we find

$$\phi_s = 0.02 \pm 0.17\,(\text{stat}) \pm 0.02\,(\text{syst})\,\text{rad},$$

where the first uncertainty is statistical and the second is systematic. In a fit to the same data in which we allow for the presence of *CP* violation in decay we find

$$\phi_s = 0.02 \pm 0.17\,(\text{stat}) \pm 0.02\,(\text{syst})\,\text{rad}, \qquad |\lambda| = 0.91\,^{+0.18}_{-0.15}\,(\text{stat}) \pm 0.02\,(\text{syst}),$$

where ϕ_s and $|\lambda|$ have a correlation coefficient of 3%. This measurement is consistent with no *CP* violation. The decay time distribution and the corresponding fit projection for the case where *CP* violation in decay is allowed are shown in Fig. 3.

In conclusion, we present the first analysis of the time evolution of flavour-tagged $\overline{B}{}^0_s \to D_s^+ D_s^-$ decays. We measure the *CP*-violating weak phase ϕ_s, allowing for the presence of *CP* violation in decay, and find that it is consistent with the Standard Model expectation and with measurements of ϕ_s in other decay modes.

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